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Ramspacher et al.

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(54) **SHAPE MEMORY ACTUATED NORMALLY OPEN PERMANENT ISOLATION VALVE**

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(73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)

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(22) Filed: **Mar. 14, 2014**

(51) **Int. Cl.**

F16K 17/14	(2006.01)
F16K 31/02	(2006.01)
F16K 31/46	(2006.01)
F02K 9/00	(2006.01)

(52) **U.S. Cl.**
CPC ***F16K 31/025*** (2013.01); ***F16K 31/46*** (2013.01); *F02K 9/00* (2013.01)

(58) **Field of Classification Search**
CPC F16K 31/025; F02K 9/00
USPC 137/68.11, 68.12, 68.14, 71
See application file for complete search history.

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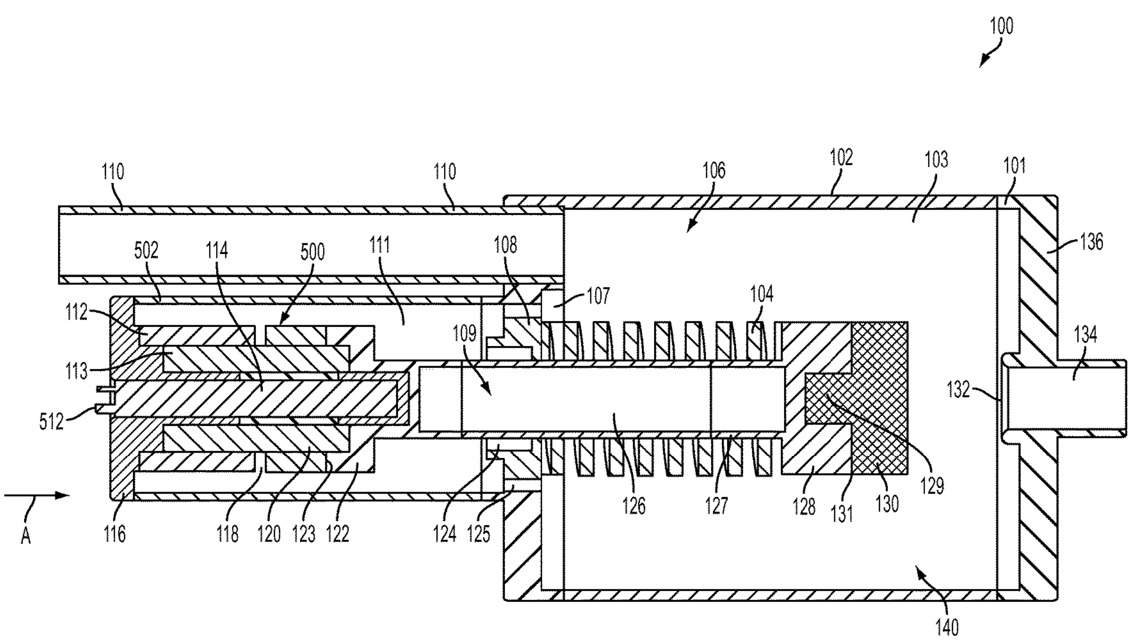
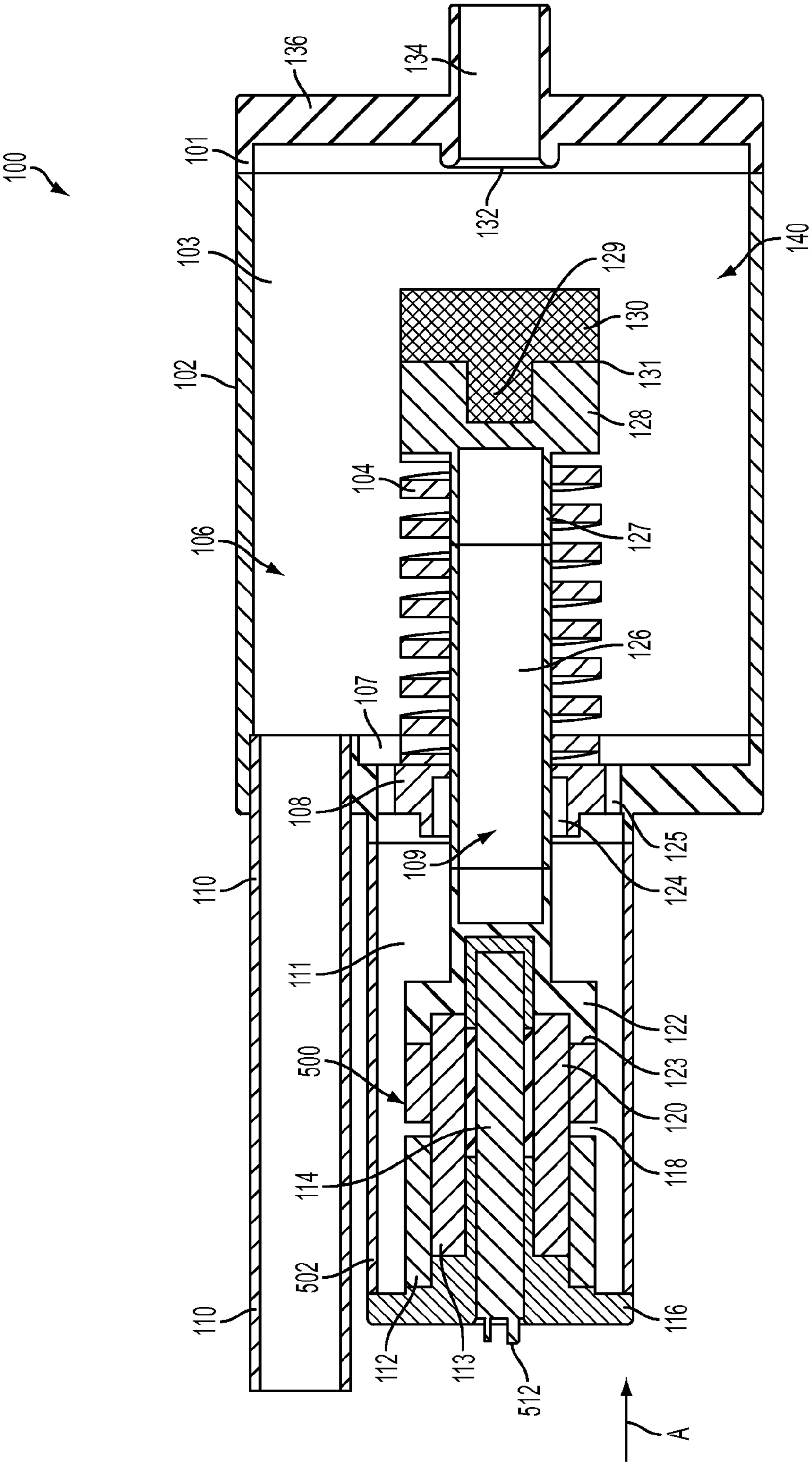
Primary Examiner — Kevin Lee
Assistant Examiner — P. Macade Nichols

(57) **ABSTRACT**

A valve assembly for an in-space propulsion system includes an inlet tube, an outlet tube, a valve body coupling the inlet tube to the outlet tube and defining a propellant flow path, a valve stem assembly disposed within the valve body, an actuator body coupled to the valve body, the valve stem assembly extending from an interior of the valve body to an interior of the actuator body, and an actuator assembly disposed within the actuator body and coupled to the valve stem assembly, the actuator assembly including a shape memory actuator member that when heated to a transition temperature is configured to enable the valve stem assembly to engage the outlet tube and seal the propellant flow path.

18 Claims, 12 Drawing Sheets

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500
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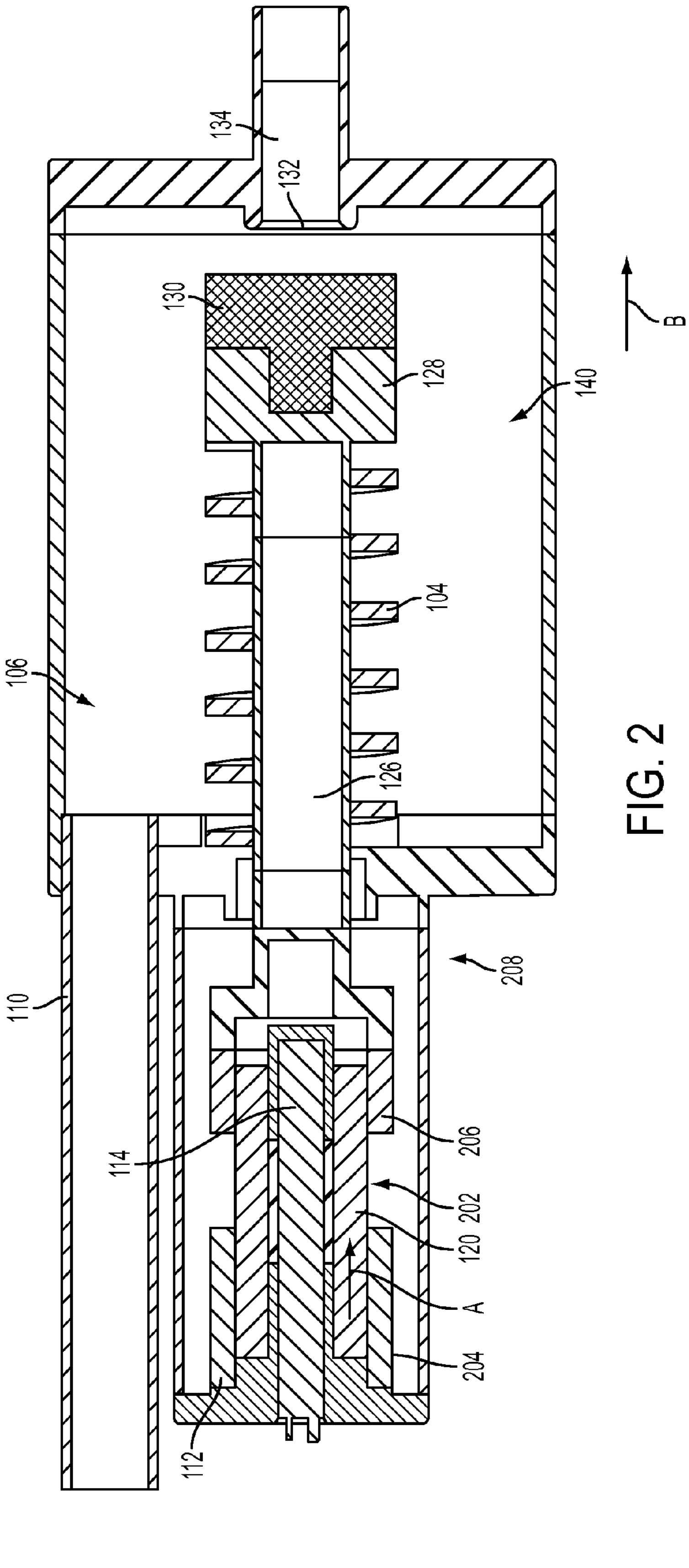
512
A

FIG. 1


134
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104
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114
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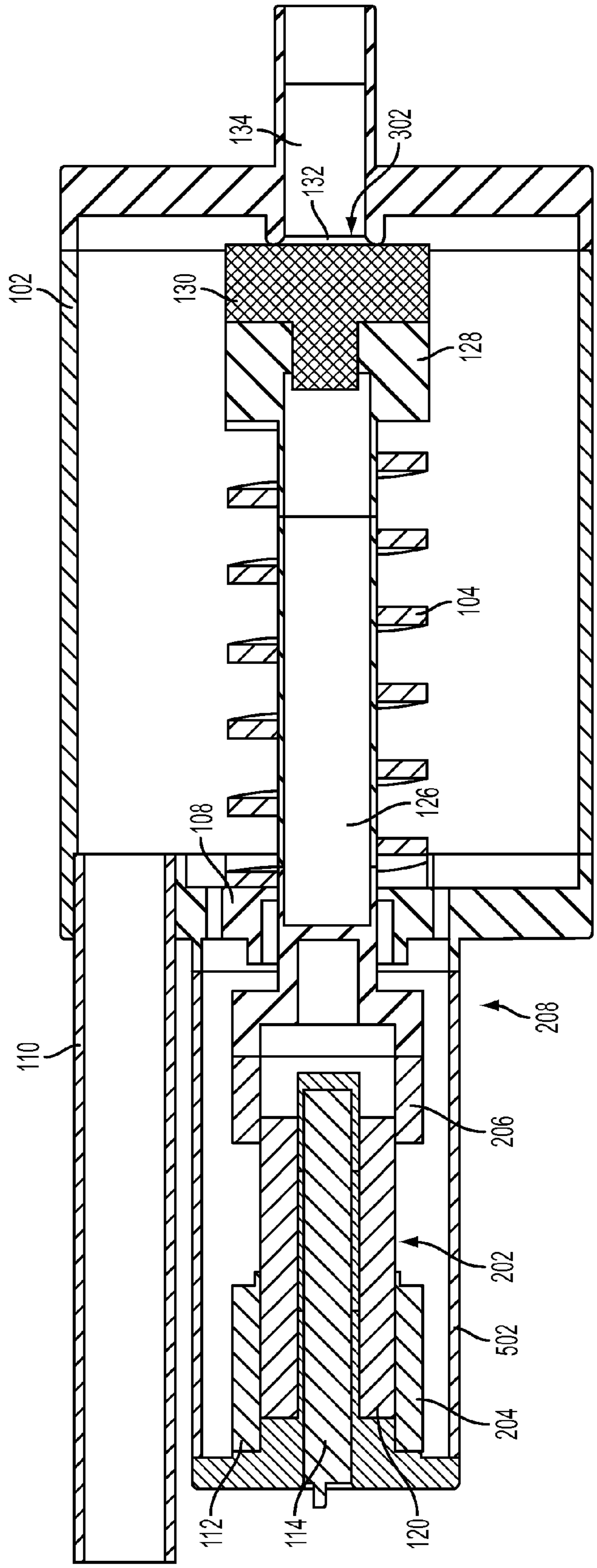
202
120
A
204
112

FIG. 2


134
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126
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112
114
120

FIG. 3

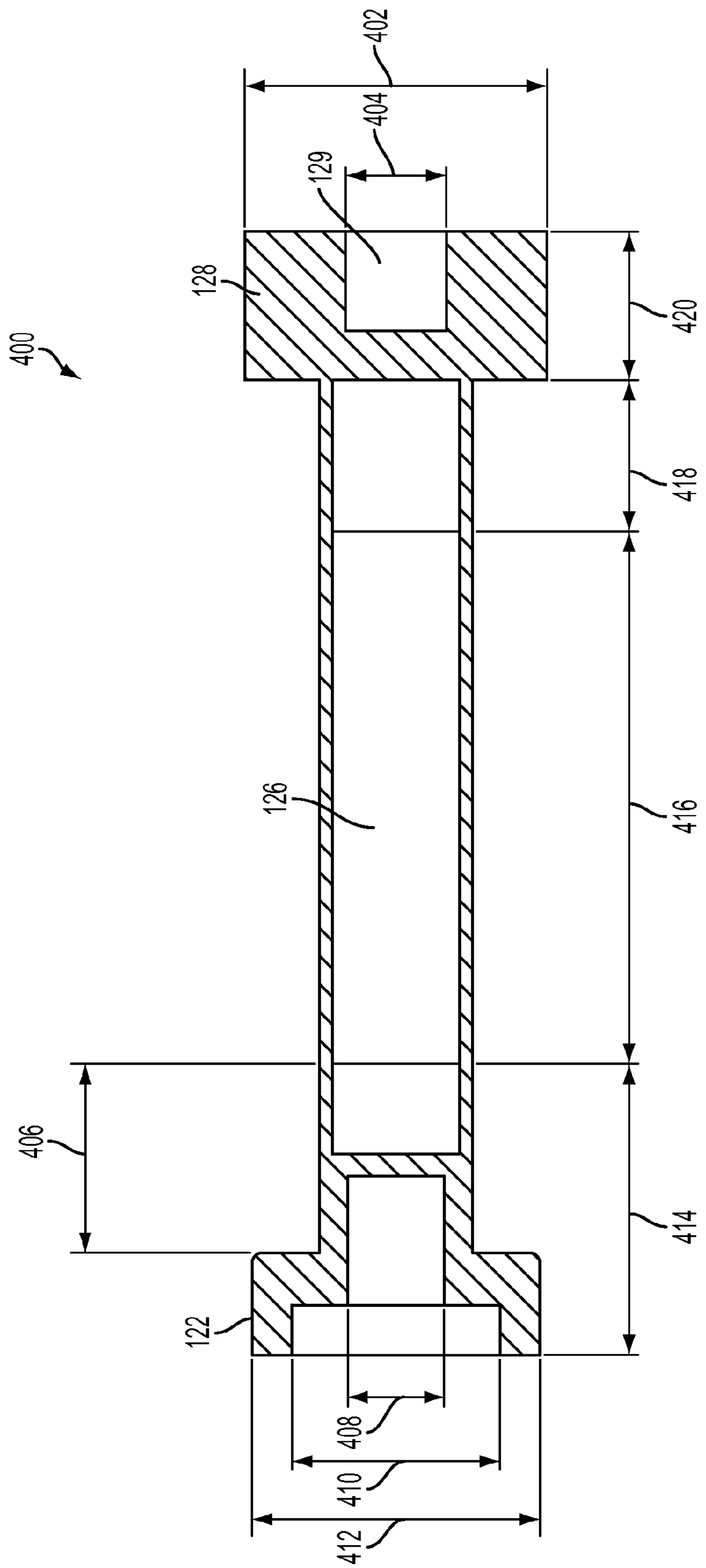
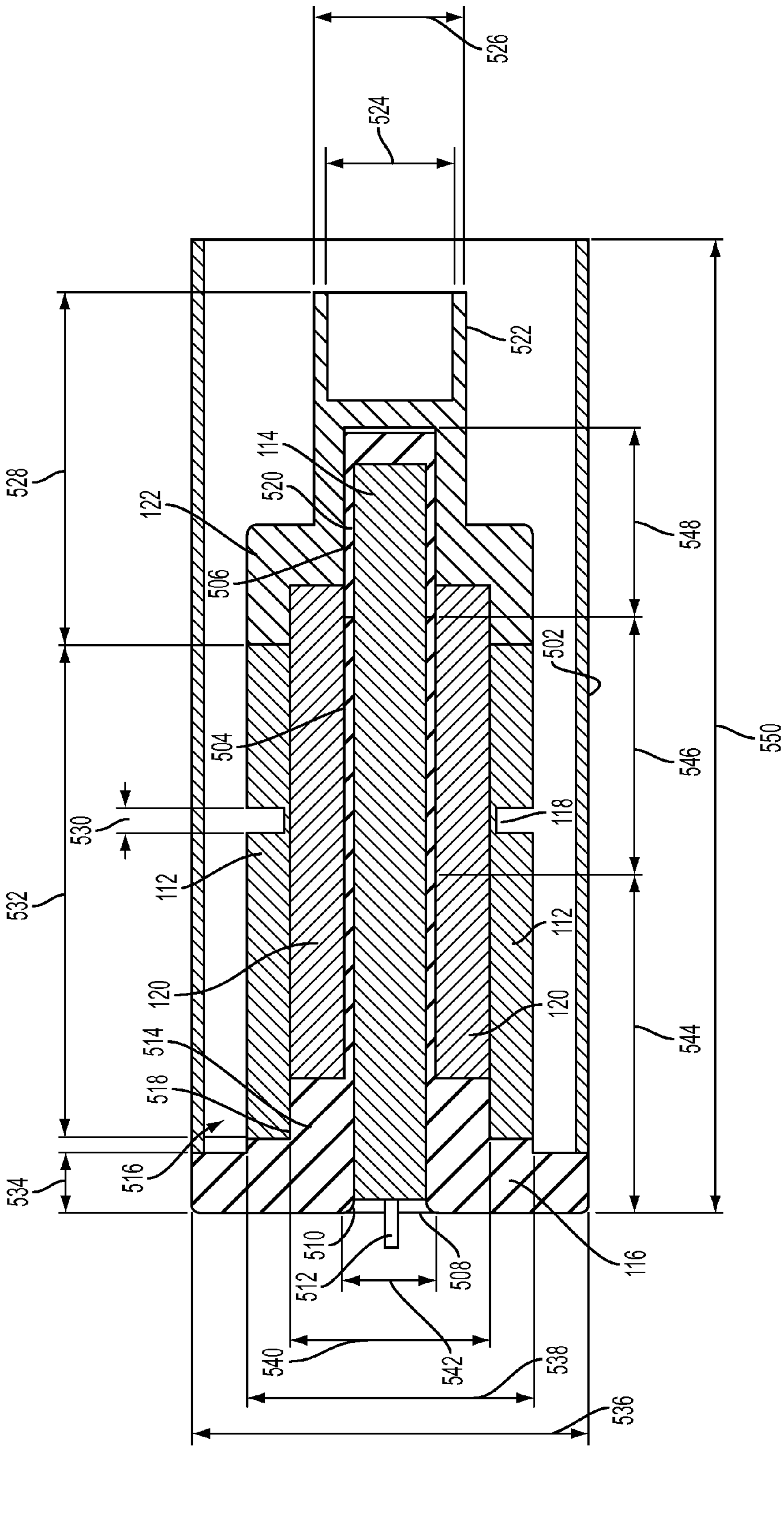


FIG. 4



526
524
522
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114
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122
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502
504
546
550
530
118
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516
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540
542
538
536

FIG. 5

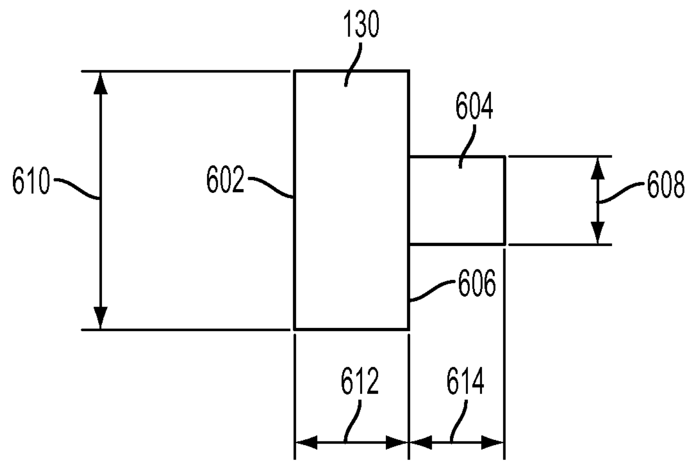

FIG. 6A

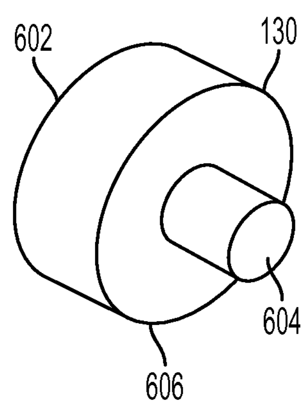

FIG. 6B

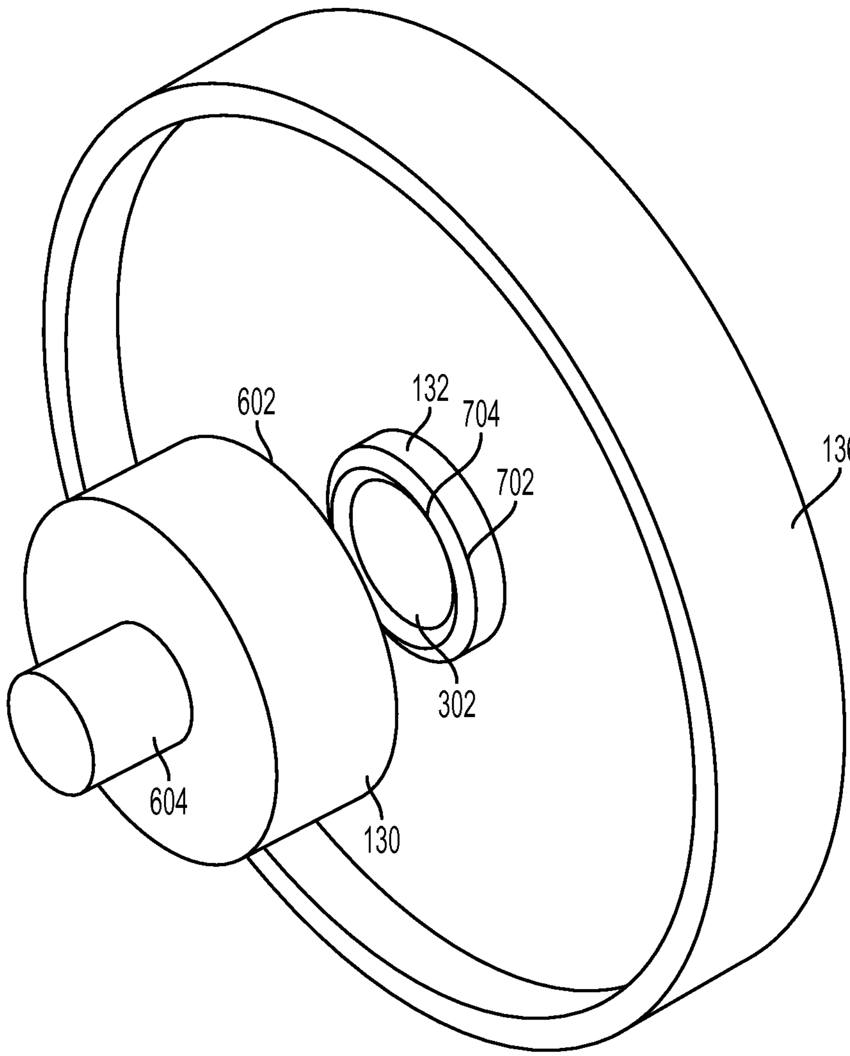

FIG. 7

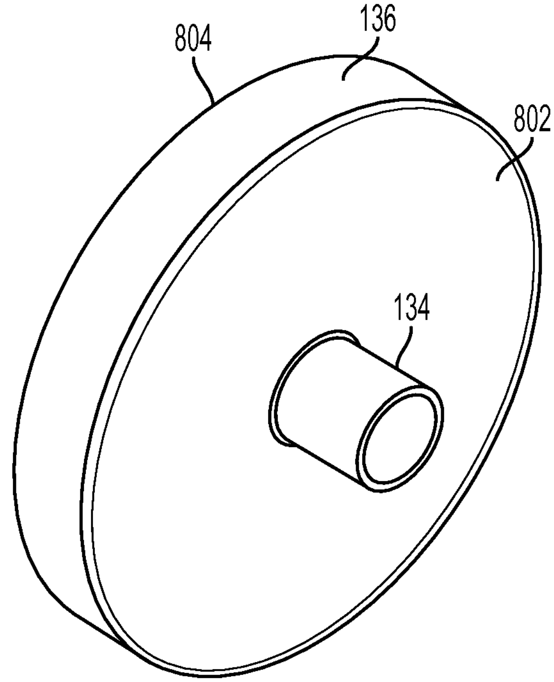

FIG. 8A

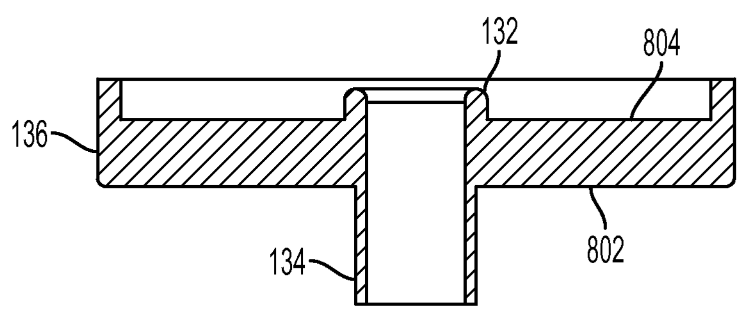

FIG. 8B

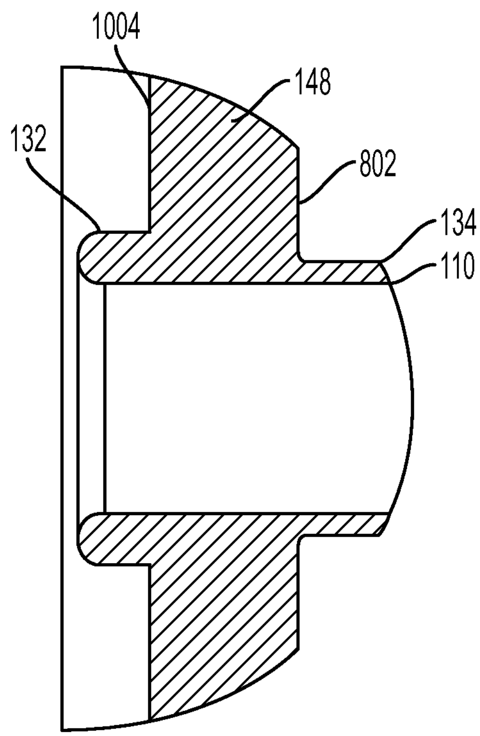

FIG. 8C

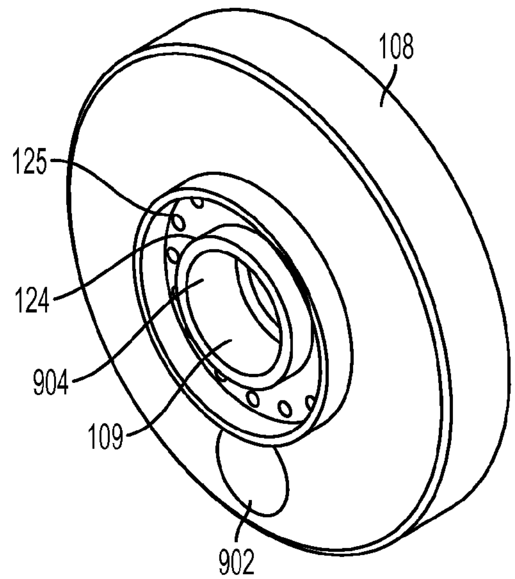

FIG. 9A

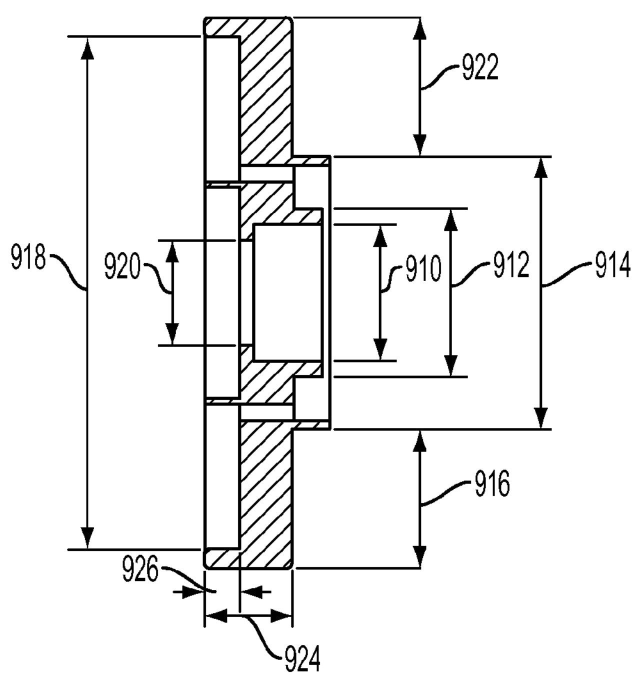

FIG. 9B

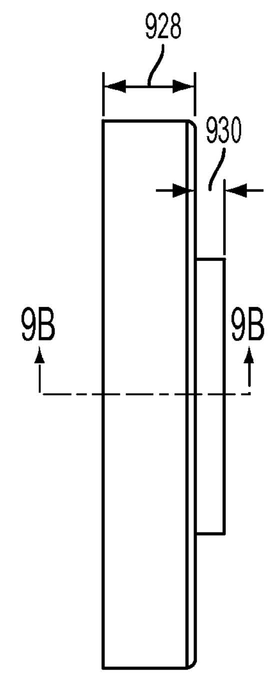

FIG. 9C

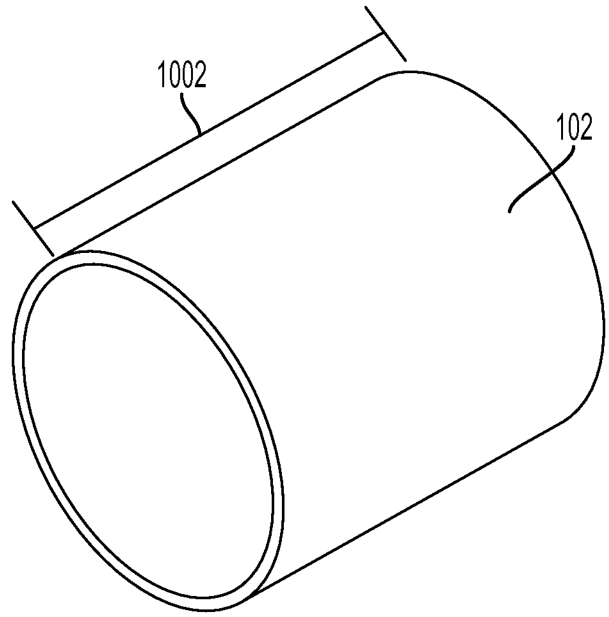

FIG. 10A

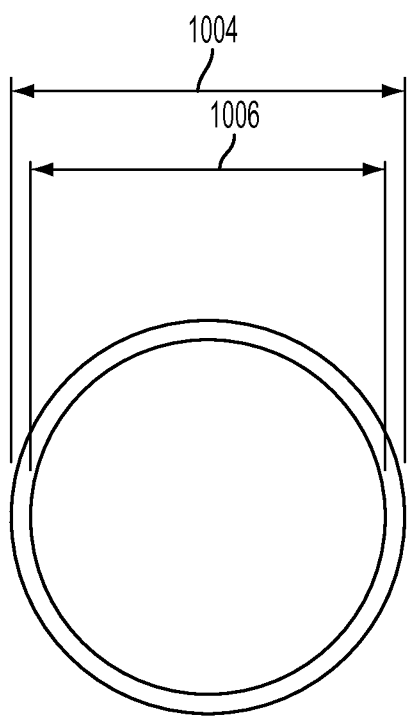

FIG. 10B

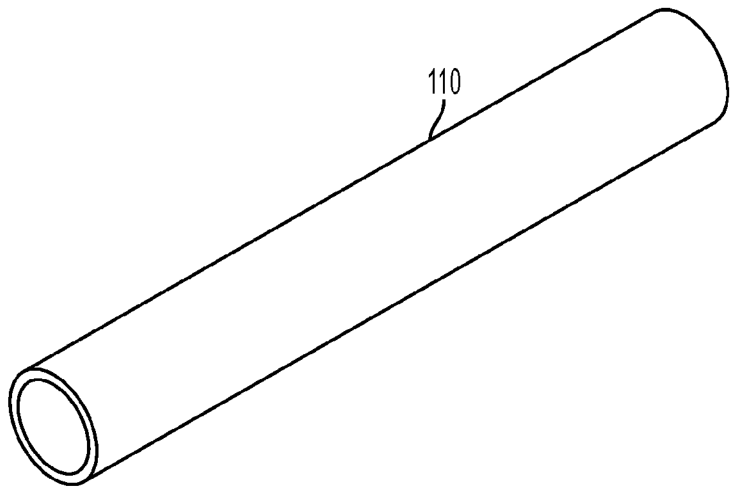

FIG. 11A

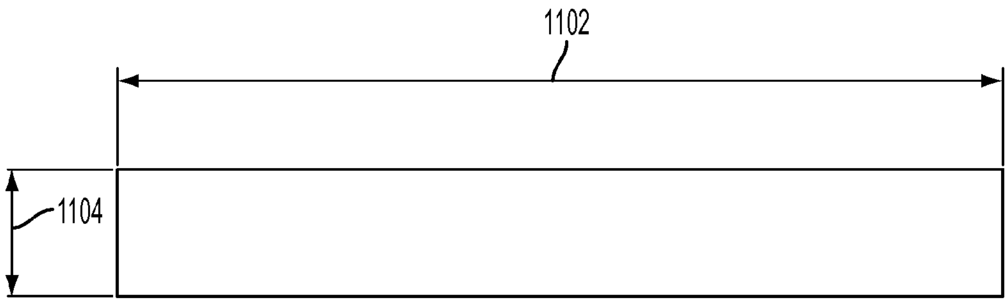

FIG. 11B

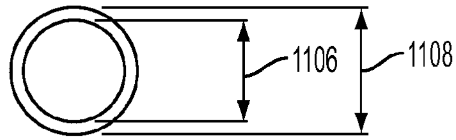

FIG. 11C

SHAPE MEMORY ACTUATED NORMALLY OPEN PERMANENT ISOLATION VALVE

ORIGIN OF INVENTION

Invention by Government Employee(s) Only

The invention described herein was made by an employee of the United States Government, and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

FIELD

The aspects of the present disclosure relate generally to permanent isolation valves for spacecraft fluid systems and, in particular, to a zero-leak permanent isolation valve for liquid propellant service in space propulsion systems.

BACKGROUND

Normally open permanent isolation valves are essential components for in-space propulsion systems. Pre-actuation, the valves must permit propellant flow. When actuated, the valves must permanently isolate sections of the propellant system that are no longer in use, preventing propellant leakage.

Potential leaks that form in a propulsion system, particularly in sections that are no longer in use, allow the propellant to escape from the system into space. These leaks limit the spacecraft performance by decreasing the system feed pressure and wasting propellant that could be used for future maneuvers, thereby shortening the mission life. Depending upon the system design, leaks could cause unwanted engine firings, crippling and potentially prematurely ending the space mission. To mitigate this liability, normally open valve assemblies are closed, permanently isolating the sections of the propulsion system downstream of the valves from the upstream propellant with a zero-leak seal. Prior to actuation, the valve allows for the flow of propellant with little pressure drop, enabling the system to operate with little or no decrease in performance.

The current aerospace industry standard for this type of valve is the pyrovalve. Pyrovalves use explosives to achieve this purpose. However, despite its widespread usage in spacecraft fluid systems, pyrovalve qualification testing has yielded unacceptably high failure rates. In some cases, the valves do not close completely. In other cases, the primary explosive fails to ignite the redundant explosive, or the explosive charges burn through the valve body. Stress corrosion is also a problem, with cracking occurring at the fillet weld of the valve.

Nickel titanium, also known as "nitinol", is a nickel and titanium metal alloy. Two properties exhibited by nitinol include shape memory and superelasticity. Shape memory, as is generally understood, is the ability of the metal alloy to undergo deformation at one temperature, and then recover its original, undeformed shape upon heating above its transformation temperature. Nitinol is a shape memory alloy that can produce up to 350 MPa of pressure to recover up to 8% strain. Nitinol can be compressed at room temperature and will recover its original shape at a transition temperature of approximately 80 degrees Centigrade. The transition temperature can be controlled by variations in the composition of the alloy. Nitinol is used as an actuator in aerospace industry components such as pin pullers and bolt cutters.

Accordingly, it would be advantageous to provide a non-explosive permanent isolation valve for spacecraft fluid systems that overcomes the problems described above.

BRIEF DESCRIPTION OF THE DISCLOSED EMBODIMENTS

As described herein, the exemplary embodiments overcome one or more of the above or other disadvantages known in the art.

One aspect of the exemplary embodiments relates a valve assembly for an in-space propulsion system. In one embodiment the valve assembly includes an inlet tube, an outlet tube, a valve body coupling the inlet tube to the outlet tube and defining a propellant flow path, a valve stem assembly disposed within the valve body, an actuator body coupled to the valve body, the valve stem assembly extending from an interior of the valve body to an interior of the actuator body, and an actuator assembly disposed within the actuator body and coupled to the valve stem assembly, the actuator assembly including a shape memory actuator member that when heated to a transition temperature is configured to enable the valve stem assembly to engage the outlet tube and seal the propellant flow path.

Another aspect of the disclosed embodiments relates to a normally open shape memory valve assembly for a spacecraft fluid system. In one embodiment, the valve assembly includes a valve body defining a fluid flow path between an inlet and an outlet, an actuator body coupled to the valve body, an actuator tube and a shape memory alloy retained within the actuator tube being disposed in the actuator body, a valve stem assembly extending from an interior of the valve body into an interior of the actuator body, the valve stem assembly including a stem cap, a seat member, and a stem shaft coupled between the stem cap and the seat member, a spring member disposed on the stem shaft, the spring member being configured to be retained in a compressed state between the valve body and the seat member, a first end of the actuator tube being coupled to the stem cap and a second end of the actuator tube being coupled to the actuator body, and a heater member retained within the actuator tube adjacent to the shape memory alloy, the heater member configured to heat the shape memory alloy to allow the shape memory alloy to expand and separate the first end of the actuator tube from the second end, enabling the spring member to drive the seat member against the outlet and seal the flowpath.

These and other aspects and advantages of the exemplary embodiments will become apparent from the following detailed description considered in conjunction with the accompanying drawings. It is to be understood, however, that the drawings are designed solely for purposes of illustration and not as a definition of the limits of the invention, for which reference should be made to the appended claims. Additional aspects and advantages of the invention will be set forth in the description that follows, and in part will be obvious from the description, or may be learned by practice of the invention. Moreover, the aspects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate presently preferred embodiments of the present disclosure, and together with the general description given above and the detailed description

given below, serve to explain the principles of the present disclosure. As shown throughout the drawings, like reference numerals designate like or corresponding parts.

FIG. **1** illustrates a cross-sectional view of one embodiment of a valve assembly incorporating aspects of the present disclosure.

FIG. **2** illustrates a cross-sectional view of one embodiment of a valve assembly incorporating aspects of the present disclosure, where the notched section is fractured.

FIG. **3** illustrates a cross-sectional view of one embodiment of a valve assembly incorporating aspects of the present disclosure, where notched section is fractured and the outlet is sealed.

FIG. **4** illustrates a cross-sectional view of one embodiment of a valve stem assembly incorporating aspects of the present disclosure.

FIG. **5** illustrates a cross-sectional view of one embodiment of an actuator assembly incorporating aspects of the present disclosure.

FIGS. **6**A-**6**B illustrate one embodiment of a seat member incorporating aspects of the present disclosure.

FIG. **7** illustrates a perspective view of one embodiment of the seat member and outlet interface in a valve assembly incorporating aspects of the present disclosure.

FIGS. **8**A-**8**C illustrate one embodiment of an outlet interface for a valve assembly incorporating aspects of the present disclosure.

FIGS. **9**A-**9**C illustrate one embodiment of an inlet valve plate for a valve assembly incorporating aspects of the present disclosure.

FIGS. **10**A-**10**B illustrate one embodiment of a valve body for a valve assembly incorporating aspects of the present disclosure.

FIGS. **11**A-**11**C illustrate one embodiment of an outlet tube for a valve assembly incorporating aspects of the present disclosure, the inlet tube being substantially similar.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS OF THE DISCLOSURE

Referring to FIG. **1**, a cross-sectional schematic view of one embodiment of a shape memory activated valve assembly **100** for a spacecraft fluid or in-space propulsion system is illustrated. The aspects of the disclosed embodiments are directed to a normally open valve assembly ("NOVA") that utilizes a shape memory alloy to limit and seal the propellant leak path through the valve assembly **100**. The valve assembly **100** of the disclosed embodiments is configured to provide a zero-leak permanent isolation valve for liquid propellant service in an in-space propulsion system. By utilizing the safe and effective properties of a shape memory alloy such as nitinol, the sealing of the valve assembly **100** is accomplished without the use of dangerous and unreliable explosives. In the examples described herein, valve assembly **100** will be described as a nitinol-actuated normally open valve assembly ("NA-NOVA"). In alternate embodiments, any suitable shape memory alloy can be used. Although the embodiments disclosed herein will be described with reference to the drawings, it should be understood that the embodiments disclosed herein can be embodied in many alternate forms. In additional any suitable size, shape or type of elements or materials could be used.

FIG. **1** illustrates one embodiment of the valve assembly **100** in a pre-actuation state. The valve assembly **100** of the disclosed embodiments generally comprises a cylindrical valve cavity or tube **102**, valve stem assembly **106**, inlet tube **110**, an actuator assembly **500** and an outlet tube **134**. The valve stem assembly **106** generally comprises a stem cap **122**, stem shaft **126**, spring cap **128** and seat or seal **130**. The actuator assembly **500** generally includes an actuator cavity body **502**, actuator tube **112** and heater element **114**. A deflected, preloaded compression spring member **104** is positioned between the seat **130** of the valve stem shaft **122** and an inlet valve plate **108**. Within the actuator tube **112** is a shape memory alloy actuator member **120** and the heater element **114**.

In the example shown in FIG. **1**, the stem shaft **126** of the valve stem assembly **106** begins in the actuator tube **112** and continues through a linear bushing **124** in the inlet valve plate **108**. The stem shaft **12** extends into the valve cavity **102**.

Prior to actuation, the valve stem assembly **106** is set away from the outlet tube **134** to allow sufficient fluid flow through the valve assembly **100**. The separation allows sufficient flow with minimal pressure drop through the valve assembly **100**. In one embodiment, prior to actuation, the valve assembly **100** allows propellant flow with a pressure drop of less than approximately 3 psi at a flow rate of approximately 0.15 kg/s.

In one embodiment, the actuator tube **112** includes a notch or notched section **118**. The notch **118** ensures a clean fracture with no particulate when the shape memory actuator **120** expands. In this example, the actuator tube **112** is a notched tube connected at one end **123** to the stem shaft **126** by the stem cap **122**. The other end **113** of the actuator tube **112** is welded to the actuator end cap **116**, fixing the initial deflection and subsequent preload of the spring member **104**. In the embodiment shown in FIG. **1**, the shape memory actuator **120** is concentric to and surrounded by the actuator tube **112**.

The linear bushing **124** is fixed into a large hole **109** in the inlet valve plate **108**, generally with an interference fit. The linear bushing **124** limits the radial float of the stem shaft **126** during actuation, ensuring that the stem shaft **126** remains centered relative to an outlet interface **132** in an outlet valve plate **136** at the outlet tube **134** end of the valve assembly **100**. The hole **109** acts as a guide for the stem shaft **126**, limiting the lateral float of the stem shaft **126** relative to the outlet interface **132**.

In one embodiment, smaller through-holes **125** are bored in the inlet valve plate **108**, connecting the actuator tube **112** to the valve cavity **102** and allowing the pressurized propellant to file a void **111** with the actuator tube **112**. The through-holes **125** enable the pressurized incompressible propellant to fill the void **111** behind the valve stem assembly **106**, balancing the hydrostatic force on the front end **140** of the valve stem assembly **106**. Without the through-holes **125**, a hydrostatic force would be exerted on the valve stem assembly **106** as it drives toward the outlet tube **134** that is substantially equal to the product of the operating pressure and the cross-sectional area of the stem cap **122**. In one embodiment, the operating pressure is less than or equal to approximately 500 psia.

Once the shape memory actuator **120** is actuated or activated, and expands to or towards its recovered state, the notch **118** in the actuator tube **112** fractures. The spring **104** begins to drive the valve stem assembly **106** towards the outlet interface **132** in the outlet valve plate **136**. Since the hydrostatic force on the front end **140** of the valve stem assembly **106** is balanced, the valve stem assembly **106** does not experience any counteracting hydrostatic force.

In one embodiment, the shape memory actuator member **120** comprises a compressed piece of nitinol, or nitinol

member, inside the valve assembly **100**. The actuator member **120** is heated when actuation is desired. By virtue of the properties of a shape memory alloy such as nitinol, when heated, the actuator member **120** recovers to its original shape. This actuation or recovery of the actuator member **120** closes the valve assembly **100**, creating a leak-tight seal. In one embodiment, the leak-tight seal can provide a leak rate of less than approximately 10^{-6} seconds (0.000001 seconds).

Actuation of the actuator member **120** is triggered by applying a voltage to the heater **114**, which heats the actuator member **120**. As shown in FIG. **1**, power can be applied to leads **512** of the heater **114**. In alternate embodiments, power can be applied in any suitable manner. Power is only applied to the valve assembly **100** during the actuation to heat the actuator member **120**. In one embodiment, the power is generally less than approximately 60 watts (W) at a voltage of less than approximately 28 volts (V), resulting in a total amount of energy of less that approximately 0.01 watt-hours (Wh).

Once the actuator member **120** reaches its transition temperature, which in this example is approximately 80 degrees Centigrade, the actuator member **120** begins to expand. As the actuator member **120** begins to expand, the axial length of the actuator member **120** increases due to the recovery. As the axial length of the actuator member **120** increases or expands, the recovering actuator member **120** applies a force, generally an axial force generally indicated by arrow A, to the actuator tube **112**. The recovering actuator member **120** continues to apply a force with an increasing magnitude as it recovers to its original, pre-compression size. The expansion of the actuator member **120** generally forces the actuator tube **112** to elongate. In one embodiment, the recovering actuator member **120** may also apply a radial force. Referring to FIG. **2**, eventually, enough force is applied to the actuator tube **112** to cause the notched section **118** of the actuator tube **112** to break or fracture. In one embodiment, the force required to fracture the notched section **118** of the actuator tube **112** is in the range of approximately 750 lbf to and including 2144 lbf.

When the notched section **118** fractures, the spring member **104** begins to drive the stem shaft **126** towards the outlet tube **134** in the direction indicated by arrow B. The example of FIG. **1** shows the valve assembly **100** prior to actuation, or before power is applied to the heater **114**. FIG. **2** illustrates an embodiment of the valve assembly **100** after the transition temperature of the actuator member **120** has been reached and the notched section **118** has fractured, driving the stem shaft **126** towards the outlet tube **134**. FIG. **2** shows the axial expansion of the spring member **104** from its pre-actuation, compressed state.

In the example illustrated in FIG. **2**, the fracture of the notched section **118** of the actuator tube **112** is generally represented by the opening **202**. In one embodiment, the notched section **118** is configured to break cleanly, without any particulates. The fracture frees the stem shaft **126**, spring cap **128**, also referred to as a poppet, and forward piece **204** of the actuator tube **112** from the aft piece **206** of the actuator tube **112**, still attached to the end **208** of the valve stem assembly **106**.

Referring to FIG. **3**, as the actuator member **120** expands, the pro-loaded spring member **104** forces the spring cap **128** with seat member **130** against the outlet tube interface **132** of the valve assembly **100**. This permanently isolates the downstream side of the valve assembly **100** from the upstream side. In this example, the downstream side can be considered the outlet tube **134**, while the upstream side can include the inlet tube **110**, valve cavity **102** and actuator body **502**. The seat member **130**, which in this example comprises a fluorinated ethylene propylene ("FEP") seat, provides a malleable surface that conforms to a size of the opening **302** of the outlet tube **134**. As the pre-loaded spring member **104** forces the seat member **130** against the outlet tube interface **132**, the seat member **130** is compressed against the opening **302**. This compression creates a leak tight seal and permanently isolates the downstream section of the valve assembly **100** from the upstream section of the valve assembly **100**. Although the seat member **130** will generally be referred to as comprising an FEP material, in alternate embodiments any suitable seat material can be used, including, but not limited to, soft materials such as Teflon, gold, copper or soft and precious metals. The seat member **130** of the disclosed embodiments provides a seal that maintains its integrity for a long duration.

After the valve assembly **100** is actuated, the propellant remains upstream of the seat member **130**. In one embodiment, the propellant downstream of the seat member **130**, or in the outlet tube **134**, is evacuated. This leaves pressurized propellant upstream of the seat member **130**, or in the valve body **102** and inlet tube **110**. Thus, there is pressurized propellant upstream and a vacuum downstream of the seat member **130**. The incompressible propellant will apply a hydrostatic force on the seat member **130** against the opening **302** of the outlet tube **134**, enhancing the sealing force provided by the spring member **104**.

FIG. **4** illustrates one embodiment of a valve stem assembly **400** for the valve assembly. The valve stem assembly **400** comprises three parts, the stem cap **122**, the stem shaft **126** and the spring cap **128**. In this example, the stem cap **122** is attached at one end of the stem shaft and the spring cap **128** at the other end. In this example, the materials of the valve stem assembly **400** generally comprise titanium and the stem shaft **126** is welded to the stem cap **122** at one end and the spring cap **128** at the other end. The stem shaft **126** is configured according to Gaseous Tungsten Arc Welding (GTAW) constraints. The total welded length of the stem shaft **126** is equal to the sum of the post actuation length of the spring **104**, the thickness of the inlet valve plate **108** and some additional clearance to ensure that the stem cap **122** does not contact the back of the inlet valve plate **108**. The post actuation length of the spring **104** can be approximately 2.148 inches, while the thickness of the inlet valve plate **108** can be approximately 0.2 inches. The additional clearance can be approximately 0.1 inches.

The table below lists exemplary dimensions for the embodiment of the valve stem assembly illustrated in FIG. **4**. The dimensions are approximate and in inches.

402	0.750
404	0.250
406	0.475
408	0.233
410	0.515
412	0.715
414	0.725
416	1.334
418	0.375
420	0.375

Referring to FIG. **5**, a cross-sectional view of one embodiment of the actuator assembly **500** for the valve assembly **100** of FIG. **1** is illustrated. In this example, the actuator assembly **500** includes the actuator tube **112**, heater member **114**, actuator end cap **116**, actuator member **120** and stem

cap **122**. Also illustrated are the actuator body **502**, heater sleeve **504** and heater sleeve cap **506**. In one embodiment, with the exception of the heater **114** and actuator member **120**, the parts of the actuator assembly **500** comprise 6AI-4V titanium, which provides a high strength-to-mass ratio and compatibility with propellants. In alternate embodiments, the actuator assembly **500** can comprise any suitable materials that provide high strength-to-mass ratio and compatibility with propellants.

The actuator end cap **116** is the part of the actuator assembly **500** that is farthest away from the valve cavity **102** shown in FIG. **1**. In one embodiment, all of the tubular components of the actuator assembly **500** are welded to the actuator end cap **116**. In alternate embodiments, the components can be coupled in any suitable manner. The through-hole **508** in the actuator end cap **116** is in-line with the hole **510** in the heater sleeve **504**, which itself is welded to the actuator end cap **116**. The through-hole **508** is open to the environment outside the valve assembly **100**, but isolated from the interior of the valve assembly **100**.

In one embodiment, the heater **114** is a cartridge heater. The heater **114**, which in one embodiment is an approximately 3/16 inch cylindrical heating element, is disposed within the through-hole **508**. The actuator member **120** is concentric to the heater sleeve **504**. In one embodiment, the actuator member **120** when compressed, has an inner diameter of approximately 0.23 inches, and outer diameter of approximately 0.50 inches, and a length of approximately 1.00 inches. The placement of the heater **114** and the concentric actuator member **120** allows for radial heat conduction through the heater sleeve **504** and into the actuator member **120**, which in this example is formed from nitinol. The aspects of the disclosed embodiments advantageously isolate the heater **114** from the inside of the valve assembly **100** and do not require the electrical leads **512** of the heater **114** to be placed through the wall of the valve assembly **100**. This allows the electrical leads **512** of the heater **114** to be easily wired into the spacecraft electrical system.

In one embodiment, the actuator tube **112** is concentric to the actuator member **120** and is welded to the actuator end cap **116**. The actuator tube **112** is a thick walled tube with a thickness of approximately 0.1 inches. An inner diameter of the actuator tube **112** is approximately 0.515 inches. A total length of the actuator tube **112** can be approximately 1.86 inches.

The following table illustrates exemplary dimensions for the lengths of the actuator end cap **116** and actuator member **120**, pre and post-actuation and the length of the actuator tube **112**, pre-actuation and at recovery.

	End Cap 116 & Actuator Member 120 (inches)	Actuator Tube 112 (inches)
Pre-actuation	1.150	1.153
Post-actuation	1.189	1.164
Total Elongation	0.039	0.011

In one embodiment, notched section of **118** of the actuator tube **112** is relatively thin-walled with a thickness of approximately 0.01 inches. A length of the notched section **118** is approximately 0.05 inches long. The notched section **118** is generally configured to provide a clean fracture with no particulates during activation.

The tubular design of the actuator assembly **500** provides for the heated sections of the actuator assembly **500**, including the actuator member **120**, heater sleeve **504** and heater **114** to be isolated from the propellant prior to fracturing of the notched section **118**. Thus, the propellant will not experience any heating from the actuator member **120**. As noted above, in the compressed state, the actuator member **120** is actuated via applied heat. In one embodiment, the actuator member **120** is thermally isolated from the rest of the spacecraft to ensure that heat conduction from other parts of the spacecraft does not cause premature actuation. The thermal isolation comes from the low thermal conductance of the titanium materials that make up the valve assembly **100**.

In one embodiment, the actuation member **120** is surrounded by a vacuum prior to actuation. The vacuum ensures that no conduction or convection occurs. Also, any radiation heat transfer is insignificant due to the small thermal gradient of the valve assembly **100**.

In the example of FIG. **5**, in one embodiment, the actuator tube **112** is welded to the actuator end cap **116**. To keep the actuator member **120** from heating to its transitional temperature during the welding process, the actuator member **120** is offset from the end of the actuator tube **112** where it is welded. As shown in FIG. **5**, in one embodiment, the actuator end cap **116** includes a raised cylindrical section **514**. The raised cylindrical section **514**, also referred to as a spacer, offsets the actuator member **120** from the end **516** of the actuator tube **112** where it is welded to the actuator end cap **116**. The offset **518** is sufficient to allow the weld to be made at a safe distance from the actuator member **120** to avoid premature actuation or recovery.

The stem cap **122** is a transition piece between the stem shaft **126** of the valve stem assembly **106** and the actuator tube **112**. In one embodiment, approximately 1/4 inch of the heater **114** inside the heater sleeve **504** is not heated. A small hole or recess **520** in the stem cap **122**, with a length of approximately 0.32 inches, allows the heater sleeve **504** and the internal unheated section of the heater **114** to protrude into the stem cap **122**. This allows the actuator member **120** to be in thermal contact with only the heated sections of the heater **114**, maximizing the heat flux to the actuator member **120**. The exemplary dimensions illustrated in the embodiment of FIG. **5** are set forth in the table below. All of the dimensions are approximate and in inches,

524	0.319
526	0.375
528	0.725
530	0.050
532	1.003
534	0.125
536	1.000
538	0.715
540	0.500
542	0.235
544	0.688
546	0.528
548	0.375
550	1.978

In one embodiment, the actuator cavity body **502** is substantially concentric to the entire actuator assembly **500**. The actuator cavity body **502** can be welded to the actuator end cap **116** and the inlet valve plate **108**. The length of the actuator cavity body **502** sets the initial deflection in the spring member **114** and its subsequent pro-load used to force the seat member **130** against the outlet interface **132** upon actuation.

Referring to FIGS. **1-5**, in one embodiment, prior to actuation, a hydrostatic load of approximately 200 lbf is applied to the valve stem assembly **106** and the actuator assembly **500** by the pressurized incompressible propellant. This hydrostatic load resists the force of the spring member **104**. Before actuation, the through-hole **125** in the inlet valve plate **108** shown in FIG. **1** allows the propellant to fill the cavity **111** between the actuator cavity body **502** and the actuator tube **112**. Once the notched section **118** is fractured during actuation, the propellant in the cavity or void **111** is free to fill the volume inside the split actuator tube **112** and balance the hydrostatic forces on the stem shaft **126**.

FIGS. **6**A and **6**B illustrates one embodiment of the seat member **130** of FIG. **1**. In this example, the seat member **130** comprises a flat edge seat member. The flat edge seat member **130** generally comprises a substantially flat, disc shaped FEP seat machined from a rod stock FEP, and includes a substantially flat side or end **602** and a rod **604**. The rod **604** extending from the end **606** of the seat member **130** is placed into the hole **129** in the spring cap **128**, shown in FIG. **1**, generally with an interference fit. Although the aspects of the disclosed embodiments are described herein with respect to a substantially flat end **602** of the seat member **130**, the aspects of the disclosed embodiments are not so limited. In alternate embodiments, any suitable seal design is contemplated, such as for example, a conical seat design. The exemplary dimensions illustrated in the embodiment of FIG. **6** are set forth in the table below. All of the dimensions are approximate and in inches.

608	0.250
610	0.750
612	0.300
614	0.250

Referring to FIG. **7**, the outlet tube interface **132** of the outlet valve plate **136** has a raised sharp edge ring member **702** that runs around the circumference of the outlet tube opening **302**, illustrated in FIG. **3**. The diameter of the face or end **602** of the seat member **130** that contacts the outlet interface **132** is larger than the outlet interface **132**. The larger diameter ensures that the seat member **130** contacts the entire area of the raised ring **702** even if some radial float occurs as the stem shaft **126** slides toward the outlet valve plate **136** during actuation.

The seal is created by pressing the substantially flat side **602** of the seat member **130** against the outlet interface **132** when the valve assembly **100** is actuated. The raised or sharp edge ring **702** of the outlet interface **132** shown in FIG. **7** digs into the seat member **130**, creating a seal. In one embodiment, a front portion or edge **704** of the raised ring member **702** has a bulbous semicircular cross-section. The FEP material of the seat member **130** is a soft material relative to the titanium of the outlet interface **132**. Thus, the seat member **130** is easily deformed as the spring **114** force presses the seat member **130** against the much harder outlet interface **132**. The FEP material of the seat member **130** will fill any surface defects in the titanium of the outlet interface **132**, effectively sealing all fluid flow pathways. Due to the small area of the seat member **130** that is in contact with the outlet interface **132**, a relatively small force is required to obtain the necessary elastic deformation in the seat member **130** to achieve a leak-tight seal. In one embodiment, the force required to create a seal is approximately 3.52 lbf, requiring 1.6 μm of deflection in the FEP material over the face **602** of the seat member **130** in contact with the ring member **702**. The surface area of the ring member **702** is large enough so that when it comes into contact with and deforms the face **602** of the seat member **130**, the seat member **130** only deforms elastically.

In one embodiment, the spring member **104** comprises a die spring. The table below provides exemplary parameters for the spring member **104**.

Design	Flat Seal Design
Spring Constant, k (lbf/in)	232
Free Length (in)	2.000
Pre-actuation Length (in)	1.284
Pre-actuation force (lbf)	166.1
Post-actuation Length (in)	1.784
Post-actuation Force (lbf)	50.1
Additional Available Deflection (in)	0.284
Rod Size (in)	0.375
Cup Size (in)	0.750

The length of the spring member **104** generally defines the length of the valve cavity tube **102**. In the example of FIG. **1**, the spring member **104** has a rod size of approximately 0.375 inches. The size of the retaining cup **522** illustrated in FIG. **5**, defines the diameter of the spring cap **122** at the end of the stem shaft **126**. The retaining cup **107** on the inlet valve plate **108** ensures that the spring member **104** remains in the correct position.

In one embodiment, the stem shaft **126** is a hollow tube to minimize its mass. An outer diameter of the stem shaft **126** can be approximately 0.375 inches, while a wall thickness of the stem shaft **126** can be approximately 0.028 inches.

The stem cap **122** comprises the transition point between the actuator tube **112** and the stem shaft **126**. The stem cap **122** serves as the bottom of the stem shaft assembly and the top of the actuator tube **112**. The top 802 of the stem cap **122** is a tube with dimensions that are substantially identical to that of the stem shaft **126**. In one embodiment, an outer diameter is approximately 0.375 inches, a wall thickness is approximately 0.028 inches and a length is approximately 0.375 inches. The length provides ample clearance for the GTAW weld head used to integrate the stem cap **122** to the stem shaft **126**. The stem cap **122** then opens up to a 0.35 inches length tube with the same diameter as the actuator tube **112** with an outer diameter of approximately 0.715 inches and a wall thickness of approximately 0.1 inches.

The spring cap **128** is the transition point between the stem shaft **126** and the seat member **130**. The spring cap **128** provides a rigid surface for the spring member **104** to contact, since the spring member **104** is disposed between the spring cap **128** and the inlet valve plate **108**. As shown in FIG. **1**, in one embodiment, the seat member **130** is integrated into the end of the spring cap **128**. The bottom **127** of the spring cap **128** has substantially identical dimensions to that of the stem shaft **126**, with an outer diameter of approximately 0.375 inches, wall thickness of approximately 0.028 inches and a length of approximately 0.375 inches. The length of the bottom **127** of the spring cap **128** provides clearance for the GTAW weld head used to integrate the stem shaft **126** to the spring cap **128**.

The other end **131** of the spring cap **128** has a diameter of approximately 0.75 inches and a length of approximately 0.375 inches. These dimensions coupled with the matching dimensions of the inlet valve plate **108** ensures that the ends of the spring **104** have a solid contact surface to contact with no overhand and minimum radial play. A bore hole **129** is

placed into the front of the spring cap **128** with a nominal diameter of approximately 0.25 inches and a depth of approximately 0.25 inches. The seat member **130** is placed into this hole **129** with an interference fit.

FIGS. **8**A-**8**C illustrate one embodiment of an outlet valve plate **136** for a valve assembly **100**. The valve outlet plate **136** is the interface between the outlet tube **134** on one side **802** and the outlet interface **132** on the opposite side **804**. The thickness of the valve outlet plate **136** is substantially the same as the thickness of the inlet valve plate **108**. In one embodiment, the thickness is approximately 0.2 inches. This thickness is sufficient to sustain the bending moment caused by the spring force without yielding. In one embodiment, the outlet tube **134** can be welded to and protrudes out of the outlet plate **136**. The end **101** of the valve cavity tube **102** shown in FIG. **1** is welded to the outlet valve plate **136** to seal the valve cavity **103** from the outside environment.

FIGS. **9**A-**9**C illustrate one embodiment of the inlet valve plate **108**. The inlet valve plate **108** has a thickness of approximately 0.2 inches. This thickness is sufficient to sustain the bending moment caused by the spring force without yielding. The inlet valve plate **108** has a nominal 0.5 inch diameter through-hole **109**. The bushing **124** shown in FIG. **1** is placed inside this hole **109** with an approximately 3/1000" interference fit. The bushing **124** is used to guide the stem shaft **126** into the outlet interface **132** during actuation. Sixteen 0.0625 inch diameter holes **125** are bored into the inlet plate **108** to allow propellant to fill the actuator cavity **111**. Once actuated and the notch **118** is fractured, the propellant is free to fill inside the fractured actuator tube **112** behind the stem shaft **126** to balance the hydrostatic force due to the pressured incompressible propellant. The inlet valve plate **108** includes an opening or recess **902** in which the inlet tube **110** is received. In one embodiment, the inlet tube **110** has a diameter of approximately 0.375 inch with 0.028 inch wall thickness. The inlet tube **110** can be welded to and protrude out of the inlet plate **108**. The valve cavity tube **102** (2.0 inch OD with 0.064 inch wall thickness) is welded to inlet valve plate **108**.

A linear bushing **124** is used between the stem shaft **126** and valve stem inlet plate **108**. The bushing **124** is configured to reduce the coefficient of friction at the valve stem inlet plate interface **904**, reducing the resistance the spring **104** must overcome during actuation, for a tighter tolerance around the stem shaft **126**, which will reduce the radial float of the stem shaft **126** during actuation.

In one embodiment, the linear bushing **124** is made from Rulon, is approximately 0.25 inches long, with an outer diameter of approximately 0.5 inches and an inner diameter of approximately 3/8 inches. The diametrical clearance between the valve stem shaft **126** and the inner diameter of the linear bushing **124** will be approximately 3/1000 of an inch. The linear bushing **124** will be placed in the inlet plate **108** with an FN 1 interference fit. This fit applies a maximum of 531 psi of compressive stress on the linear bushing **124**, which is below its compressive yield strength of approximately 1000 psi.

The exemplary dimensions illustrated in the embodiment of FIGS. **9**B and **9**C are set forth in the table below. All of the dimensions are approximate and in inches.

910	0.500
912	0.600
914	1.000
916	0.500
918	1.872

-continued

920	0.375
922	0.500
924	0.300
926	0.125
928	0.325
930	0.125

FIGS. **10**A-**10**B illustrates one embodiment of the valve cavity body or tube **102**. The valve cavity tube **102** isolates the main internal section of the valve or valve cavity **103** from the outside environment. In one embodiment, the valve cavity tube **102** has an outer diameter of approximately 2.0 inches, a wall thickness of approximately 0.028 inches, and a length of approximately 2.305 inches. In alternate embodiments, any suitable dimensions for the valve cavity tube **102** can be used. The diameter of the valve cavity tube **102** is chosen to meet the pressure drop requirements. The length of the valve cavity tube **102** sets the initial separation between the seat **130** and the outlet interface **136**, or the stroke length of the valve assembly **106**. In one embodiment, the total length of the valve cavity tube **102** is equal to the sum of the pre-actuation length of the spring **104**, the length of spring cap **128**, the length of the seat **130** and the stroke length. In the example of FIG. **1**, this length is approximately 2.555 inches.

The exemplary dimensions illustrated in the embodiment of FIGS. **10**A-**10**B are set forth in the table below. All of the dimensions are approximate and in inches.

1002	2.305
1004	2.000
1006	1.872

FIGS. **11**A-**11**C illustrate one embodiment of the inlet tube **110**. The outlet tube **134** of FIG. **1** looks substantially the same. In one embodiment, the diameter and wall thickness of both the inlet tube **110** and the outlet tube **134** are approximately 0.375 inches and 0.028 inches, respectively. The inlet and outlet tubes **110**, **134** can have lengths of approximately 2.7 inches and 0.3125 inches respectively. This length allows the valve assembly **100** to be easily integrated into propellant lines of a propulsion system using the gaseous tungsten arc welder typically used in spacecraft integration. The diameter of 0.375 inches is typical of spacecraft propellant lines. In alternate embodiments, the valve assembly **100** can be used with other sized propellant lines with the use of transition tubes that neck up or down to the necessary tubing diameter and wall thickness.

The exemplary dimensions illustrated in the embodiment of FIGS. **11**A-**11**C are set forth in the table below. All of the dimensions are approximate and in inches.

1102	2.700
1104	0.375
1106	0.319
1108	0.375

The wall thicknesses of the valve assembly **100** are derived from the burst pressure requirement (1250 psi). At this pressure, the required wall thickness-to-radius is 0.01. The following table shows the wall thickness of each tubular section of the valve assembly **100** and its respective safety factor.

Part	Radius, r (in)	Thickness, t (in)	Required Thickness (in)	Safety Factor
Valve Body/ Cavity Tube 102	1.00	0.064	0.01	6.4
Actuator Body/ Cavity Tube 502	0.5	0.032	0.005	6.4
Heater Sleeve 504	0.115	0.02275	0.00115	19.8
Inlet/Outlet Tubes 110/134	0.1875	0.028	0.001875	14.93
Stem Shaft 126	0.250	0.028	0.0025	11.2
Notch 118	0.2675	0.010	0.002675	3.74
Actuator Tube 112	0.3575	0.100	0.003575	27.97

All safety factors are greater than 1 to ensure that no components will fail at the burst pressure. The thin wall thicknesses minimize mass of the valve assembly **100**.

The aspects of the disclosed embodiments provide a normally open permanent isolation valve for an in-space propulsion system. In one embodiment, the valve assembly **100** can be used as a drop in replacement for the currently used pyrovalve. The actuator **120** comprises a compressed hollow cylinder of nitinol and a cartridge housing placed concentrically inside the actuator cavity body **502**. A spring **104** of the valve assembly **100** is compressed between the valve body **102** and an end of the valve stem **126** that includes a seat or seal **130**. When the actuator **120** is actuated, the spring **104** expands driving the seat **130** into an outlet interface **136**, sealing the valve assembly **100**. The seat **130** is a fluorinated ethylene propylene (FEP) seal that is pressed against a bulbous annulus at the outlet interface **136** of the valve assembly **100**. The valve assembly **100** of the disclosed embodiments thus provides a leak-tight seal without the use explosive actuators and is generally compatible with all storable propellants.

Thus, while there have been shown, described and pointed out, fundamental novel features of the invention as applied to the exemplary embodiments thereof it will be understood that various omissions and substitutions and changes in the form and details of devices and methods illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit of the invention. Moreover, it is expressly intended that all combinations of those elements and/or method steps, which perform substantially the same function in substantially the same way to achieve the same results, are within the scope of the invention. Moreover, it should be recognized that structures and/or elements and/or method steps shown and/or described in connection with any disclosed form or embodiment of the invention may be incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

What is claimed is:

1. A valve assembly for an in-space propulsion system, comprising:

an inlet tube;

an outlet tube;

a valve body coupling the inlet tube to the outlet tube and defining a propellant flow path;

a valve stem assembly disposed within the valve body;

an actuator body coupled to the valve body, the valve stem assembly extending from an interior of the valve body to an interior of the actuator body;

an actuator assembly disposed within the actuator body and coupled to the valve stem assembly, the actuator assembly comprising a shape memory actuator member that when heated to a transition temperature is configured to enable the valve stem assembly to engage the outlet tube and seal the propellant flow path; and

a spring member disposed along the valve stem assembly between a seat member of the valve stem assembly and the valve body, the spring member being retained in a compressed state between the seat member and the valve body;

wherein the actuator assembly comprises an actuator tube assembly housing the shape-memory actuator member, the actuator tube assembly being coupled to the actuator body on one end and the valve stem assembly on another end.

2. The valve assembly of claim **1**, the actuator tube assembly including a notched section, a first portion of the actuator tube assembly on one side of the notched section being coupled to the actuator body, a second portion of the actuator tube assembly on another side of the notched section being coupled to the valve stem assembly, the notched section configured to fracture to release the coupling of the valve stem assembly from the actuator body through the actuator tube assembly.

3. The valve assembly of claim **1**, wherein the spring member is configured to expand when a notched section fractures and drive the seat member towards the outlet tube to seal the flow path.

4. The valve assembly of claim **1**, wherein the outlet tube comprises an outlet interface that is configured to mate with the seat member and form a leak tight seal in the flow path.

5. The valve assembly of claim **4**, wherein the outlet interface comprises a raised member that is configured to sealingly engage a face of the seat member.

6. The valve assembly of claim **1**, comprising a heater member disposed within the actuator tube assembly and configured to heat the shape memory actuator member.

7. A valve assembly for an in-space propulsion system, comprising:

an inlet tube;

an outlet tube;

a valve body coupling the inlet tube to the outlet tube and defining a propellant flow path;

a valve stem assembly disposed within the valve body;

an actuator body coupled to the valve body, the valve stem assembly extending from an interior of the valve body to an interior of the actuator body;

an actuator assembly disposed within the actuator body and coupled to the valve stem assembly, the actuator assembly comprising a shape memory actuator member that when heated to a transition temperature is configured to enable the valve stem assembly to engage the outlet tube and seal the propellant flow path; and

an inlet valve plate coupled to an end of the valve body between the valve body and the actuator body, the inlet valve plate securing the actuator body to the valve body, the inlet valve plate comprising a through hole to allow a flow of propellant from the interior of the valve body to the interior of the actuator body.

8. The valve assembly of claim **7**, wherein the shape memory actuator member comprises a NITINOL-nickel titanium shape memory alloy member.

9. A normally open shape memory valve assembly for a spacecraft fluid system comprising:

a valve body defining a fluid flow path between an inlet and an outlet;

an actuator body coupled to the valve body, an actuator tube and a shape memory alloy retained within the actuator tube being disposed in the actuator body;

a valve stem assembly extending from an interior of the valve body into an interior of the actuator body, the valve stem assembly comprising a stem cap, a seat member, and a stem shaft coupled between the stem cap and the seat member;

a spring member disposed on the stem shaft, the spring member being configured to be retained in a compressed state between the valve body and the seat member;

a first end of the actuator tube being coupled to the stem cap and a second end of the actuator tube being coupled to the actuator body; and

a heater member retained within the actuator tube adjacent to the shape memory alloy, the heater member configured to heat the shape memory alloy to allow the shape memory alloy to expand and separate the first end of the actuator tube from the second end, enabling the spring member to drive the seat member against the outlet and seal the flowpath.

10. The normally open shape memory valve assembly of claim **9**, wherein when the spring member is in a compressed state, the seat member is positioned away from the outlet.

11. The normally open shape memory valve assembly of claim **9**, wherein the actuator tube comprises a fracturable notched section between the first end and the second end, and the expansion of the shape memory alloy fractures the notched section to separate the first end from the second end.

12. The normally open shape memory valve assembly of claim **11**, wherein the fracturable notched section couples the first end of the actuator tube to the second end of the actuator tube to retain the spring member in the compressed state.

13. The normally open shape memory valve assembly of claim **9**, wherein a wall of the valve body includes an opening to allow the passage of the stem shaft between the valve body and the actuator body and a through hole to allow a passage of fluid from the valve body into the actuator body.

14. The normally open shape memory valve assembly of claim **9**, wherein the outlet comprises a ringed member extending away from the outlet and configured to engage the seat member and seal the outlet in a non-compressed state of the spring member.

15. The normally open shape memory valve assembly of claim **9**, wherein the second end of the actuator tube comprises a raised cylindrical portion separating the shape memory alloy from a weld point on the second end of the actuator tube.

16. The normally open shape memory valve assembly of claim **9**, wherein the valve stem assembly comprises a spring cap between the spring member and the seat member, the spring cap being fixedly secured to the stem shaft and the seat member retained by the spring cap.

17. The normally open shape memory valve assembly of claim **16**, wherein the spring cap comprises a titanium alloy and the seat member comprises a fluorinated ethylene propylene material.

18. The normally open shape memory valve assembly of claim **9**, wherein the shape memory alloy is NITINOL-nickel titanium.

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